

A STUDY OF STRAIN-INDUCED PHASE TRANSFORMATIONS IN TiNi ALLOY BY ELECTRIC RESISTANCE METHOD

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INTRODUCTION

It is generally recognized that the shape memory effect (SME) is associated the interaction of stress with thermoelastic martensitic transformation [1]. The phase transformations in TiNi alloy was reported to occur as three kinds of B2→R, B2→M, R→M phase transformations [2]. There are different views about premartensitic transformation in TiNi based alloys. Muang et al [3] reported a transformation sequence in TiNiFe alloy that was the parent B2→Incommensurate I→Rhombohedra R→Martensite M. But many authors [2,4] reported that the premartensitic structure of TiNi alloy is rhombohedra. It is known that the electric resistance increase in the premartensitic transformation range was because of the R-phase taking affect. The electric resistance decrease below the temperature M_s was because of the martensite occurrence. It is not clear what occurred when the SME alloy is made a plastic deformation. Muang et al [5] was reported that in a TiNi alloy the new rhombohedral phase, perhaps, was induced by stress in the internal friction experiment. In this paper the phase transformation induced by the plastic deformation was studied by the electric resistance method.

EXPERIMENTS

The specimen of TiNi alloy was supplied by the Research Institute of Nonferrous Metals, Ministry of Metallurgical Industry, Beijing. The composition was Ni-55.3wt%, Ti-44.7wt%. The diameter of the specimen is 0.718 mm and the length is about 110 mm. This specimen has been studied by internal friction, electric resistance and shape change which was measured synchronously [5]. Now, we study the electric resistance R as a function of plastic deformation at constant temperature. The plastic deformation was made using a torsional set. The low terminal of the specimen was fixed in the torsional set, and the upper terminal was connected with an indicative system which can make torsional plastic deformation and the deformation angle ϕ measurements conveniently. The torsional strain γ can be calculated by

$$\gamma = \frac{r\phi}{l}$$

where l is the length of the specimen and r is the distance between the strain place and the axis. The torsional strain γ at the surface of the specimen wire is about 1.1% when the plastic deformation angle $\phi = 180^\circ$. Therefore we can use to the angle ϕ to represent the torsional strain γ . This method has more advantage than the bending method that was used in most experiments with a shape memory effect [2,5].

The torsional set is inserted in a Dewar flask and different temperature water or the mixture of alcohol and dry ice were poured into it. The temperature can be held constant at about $\pm 0.1^\circ\text{C}$ for one hour. The procedures of the experiment were:

(1) The TiNi wire was heated to $+80^\circ\text{C}$ and followed by cooling to a different constant temperature.

(2) The specimen was made torsional plastic deformation from 0° to about 600° and measure the angle ϕ and the resistance R at the same time.

The R was measured by the D.C. method using a four-point terminal connection.

(3) After every $(R \sim \phi)_T$ curve measurement, the TiNi wire was heated to $+80^\circ\text{C}$ and the shape memory effect was observed. Followed the specimen as cooled to other constant temperature and repeat the above measurements.

RESULTS

These results as shown in Fig. 1,2. are a group of $(R \sim \phi)_T$ curves from temperature $+46^\circ\text{C}$ to -39°C . These curves have supplied much new information about the phase transformations that are induced by plastic deformation. These curves show that the resistance R (Ω) is changed with the plastic deformation ϕ .

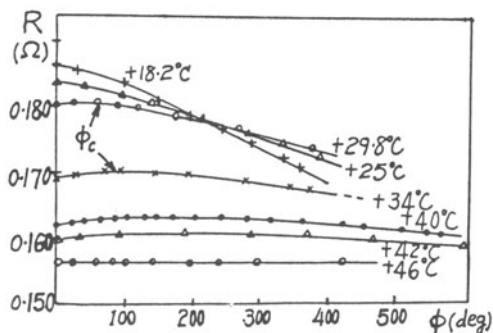


Fig. 1. The electric resistance R (Ω) as a function of the plastic deformation angle ϕ at constant temperature above M_s .

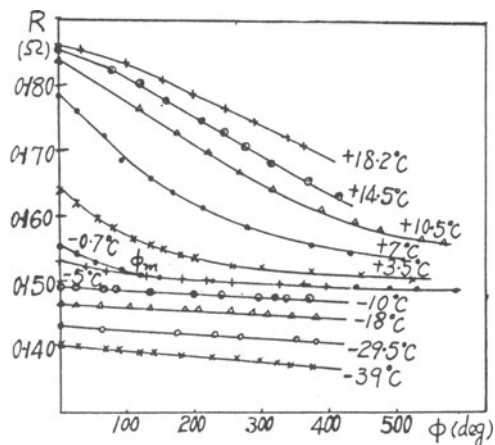


Fig. 2. The electric resistance R (Ω) as a function of the plastic deformation angle ϕ at constant temperature below M_s .

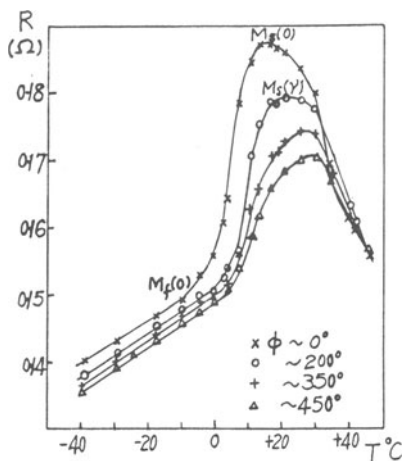


Fig. 3. The electric resistance $R(\Omega)$ as a function of temperature T at constant plastic deformation angle $\phi = 0^\circ, 200^\circ, 350^\circ$ and 450° .

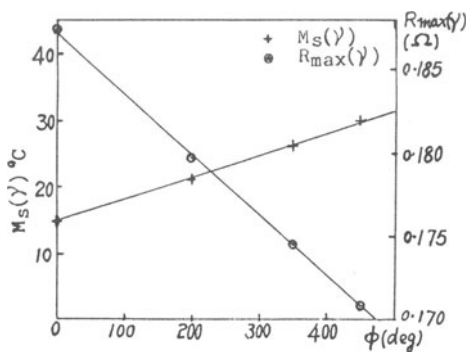


Fig. 4. The start temperature $M_s(\gamma)$ of the martensitic transformation influenced by ϕ and the peak values $R_{\max}(\gamma)$ in Fig. 3. as a function of plastic deformation ϕ respectively.

DISCUSSIONS

The resistance change reflects the phase transformation that is induced by plastic deformation because the measurement of every curve was at constant temperature. The explanation of these results are more complex because the phase transformation are complex in this temperature range. The following are our rough explanations:

(1) The $+46^\circ\text{C}$ curve of $(R \sim \phi)$ in Fig. 1. is a horizontal straight line. It is meant that the phase transformation cannot be induced by the plastic deformation when the temperature is equal to or above $+46^\circ\text{C}$. This temperature is just the A_s [5] so that the limited temperature M_d of strain-induced martensite may be almost equal to A_s in TiNi alloy. This electric resistance measurement is a favorable method to determine the M_d .

(2) New R-phase can be induced by plastic deformation:

We denote the strain-induced R-phase by R_e (SIR) and the strain-induced M-phase by M_e (SIM), the thermodynamical R-phase by R_T , the thermoelastic martensite by M_T .

The $(R \sim \phi)$ curves of $+29.8$, $+34$, $+40$ and $+42^\circ\text{C}$ in Fig. 1, have a resistance peak. The height of the resistance peak is little but the appearance obviously compares to the resistance of $\phi = 0$. This result can only be explained by the R-phase R_e being induced by the plastic deformation. When the plastic deformation increases over the peak value ϕ_c , the resistance begins decreasing because of the M_e (SIM) being induced. The peak value ϕ_c (see Fig. 1) may be considered as the critical plastic deformation to induce the M_e . This consideration is in agreement with the point of view of Dejonghe [6].

(3) The start temperature M_s of the martensitic transformation can be influenced by the plastic deformation:

Fig. 3. was deduced from Fig. 1,2. that shows the resistance R as a function of temperature T at constant ϕ . The ($R \sim T$) curves of $\phi = 200^\circ, 350^\circ, 450^\circ$ is below the $\phi = 0$ curve in the temperature range from -40°C to about $+30^\circ\text{C}$. We believe this is because of the thermodynamical R - phase R_T decreasing and it transforms to the strain-induced martensite M_ϵ .

The peak temperature of $\phi = 0$ curve in Fig. 3 is the start temperature $M_s(0)$ of the martensitic transformation without the plastic deformation. The peak temperatures of $\phi = 200^\circ, 350^\circ, 450^\circ$ curves may be considered as the start temperature $M_s(\gamma)$ of the martensitic transformation influenced by plastic deformation. At these temperatures the thermoelastic martensite begins to occur because of the plastic deformation ϕ that helps the drive force of the thermodynamics so that the $M_s(\gamma)$ is raising more than $M_s(0)$. The relation between the plastic deformation ϕ and $M_s(\gamma)$ is a straight line as shown in Fig. 4. and can be expressed as

$$M_s(\gamma) = A\phi + M_s(0) \quad (1)$$

where the A is a constant that is equal to $1/30$ (K/deg). It is meant that one degree of the plastic deformation ϕ can influence the $M_s(\gamma)$ to increase $1/30$ K.

The relation between the electric resistance peak values $R_{\max}(\gamma)$ and the plastic deformation ϕ is also a straight line in Fig. 4. and can be expressed as

$$R_{\max}(\gamma) = B\phi + R_{\max}(0) \quad (2)$$

where the B is a constant that is equal to -0.40×10^{-4} (Ω/deg). Let us suppose that the amount of strain-induced martensite M_ϵ is proportional to the difference of the resistance peak value $\Delta R_{\max}(= R_{\max}(0) - R_{\max}(\gamma))$, we conclude that the amount of M_ϵ is proportional to the plastic deformation. This supposition is only fit to the amount of M_ϵ that is transformed from the rhombohedra by the plastic deformation. This explanation of empiric formula (2) is not perfect and must be studied in advance.

Equation (1) is in agreement with the theoretical result from the thermodynamics of thermoelastic martensitic transformations [7]. According to the T-W model of the thermoelastic martensitic transformation, the driving force of free energy is a function of temperature T and stress σ , can obtain

$$M_s(\sigma) = C\sigma + M_s \quad (3)$$

This theoretical result is confirmed by our experiment. This means that the driving force influenced by torsional plastic deformation is identical to the stress σ .

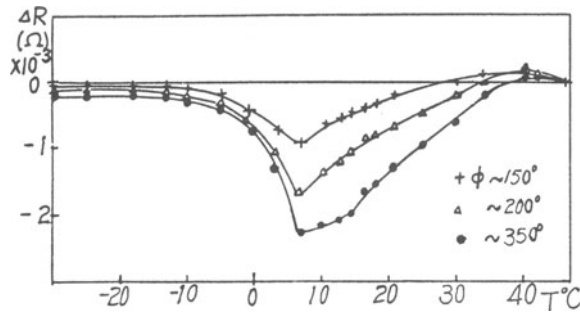


Fig. 5. The electric resistance difference ΔR that induced by the constant $\phi = 150^\circ, 200^\circ, 350^\circ$ as a function of temperature.

(4) The strain-induced martensite M_ϵ was induced easily by the plastic deformation in the temperature range from $M_s (=15^\circ\text{C})$ to $M_f (-9^\circ\text{C})$.

The $+7^\circ\text{C}$ curve in Fig. 2. exhibits maximum slope down and means that the M_ϵ was induced easily by the plastic deformation. This result is also shown in Fig. 5. that the curves of resistance difference $\Delta R (= R - R_0 = 0)$ as a function of T exhibit a negative peak at $+7^\circ\text{C}$. It was reported [5] that at this temperature the martensitic transformation internal friction peak P_{C3} occurred and is associated with the $-\partial R / \partial T = \max$ and the shape change $-\partial X / \partial T = \max$. Now, the $-\partial R / \partial \phi = \max$ occurred at this temperature.

The $-5^\circ\text{C}, -0.7^\circ\text{C}, +3.5^\circ\text{C}, +7^\circ\text{C}, +10.5^\circ\text{C}$ curves in Fig. 2. show that the electric resistance R vary exponentially with ϕ in the starting stage and after a certain value ϕ_m it is a straight line. It is known that the $B2 \rightarrow M_\epsilon$ transformation can be induced by the strain in this temperature range, but the dynamic law of this transformation is not known. Now, we can obtain an experimental dynamic law of the $B2 \rightarrow M_\epsilon$ transformation. The relation between resistance, plastic deformation and temperature can be obtained as following:

Perhaps, the starting stage of ϕ can be taken in the relations as

$$R = C' e^{-b\phi} \quad (4)$$

Let us take the natural logarithms of R ($= \ln R$) as a function of ϕ in a temperature range from -5°C to $+13^\circ\text{C}$. Fig. 6 shows a group of straight lines in the start stage of ϕ and means that the equation

$$\ln R = \ln C' - b\phi$$

obtained from Fig. 6. is true. When $\phi = 0$, the constant C' is equal to $R = 0$. Equation (4) becomes

$$R = R_0 = 0 \exp(-b\phi) \quad (5)$$

where the b is a function of temperature that can be obtained from

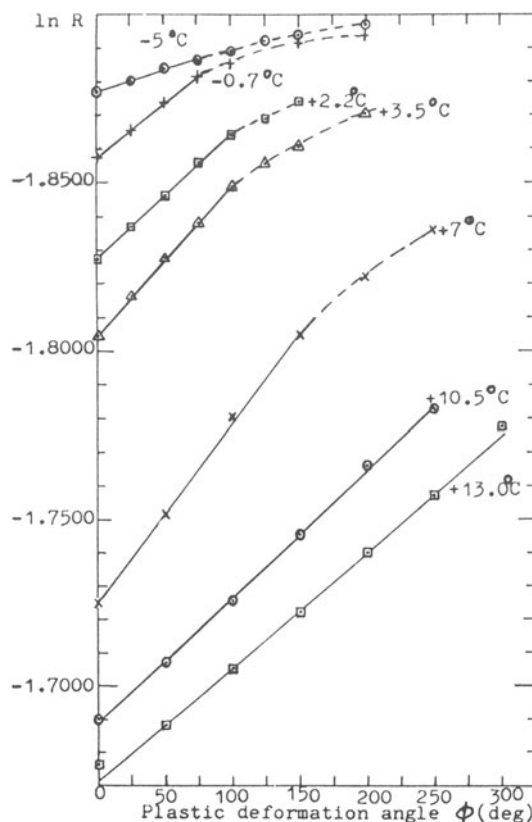


Fig. 6. The diagram shows the $\ln R$ as a function of the plastic deformation in temperature range from -5°C to $+13^{\circ}\text{C}$. In the start stage of ϕ are a group of straight lines and means that the equation $R=C' \exp(-b\phi)$ is true.

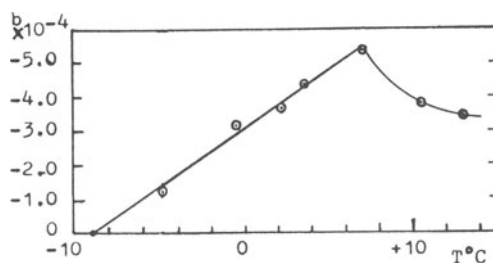


Fig. 7. The diagram shows the slopes b of the straight lines in Fig. 6. as a function of temperature $T^{\circ}\text{C}$ (or T K). The $(b-T)$ curve is a straight line below $+7^{\circ}\text{C}$. When $b = 0$, the temperature is -9°C that is equal to the $M_f(0)$ (see Fig. 3.).

Fig. 7. The $b = \Delta \ln R / \Delta \phi$ are the slopes of straight lines in Fig. 6. The slope b as a function of $T^{\circ}\text{C}$ (or T K) below $+7^{\circ}\text{C}$ is a straight line and the equation is

$$b = mT + C''$$

When $b = 0$, $C'' = -mM_f(0)$ (see Fig. 7.). Finally, equation (5) can be expressed as

$$R = R_{\phi=0} \exp(-m(T-M_f(0))\phi) \quad (6)$$

Equation (6) can be considered as the dynamic law of the martensite M induced by the plastic deformation from B2 phase at different temperatures from $+7^\circ\text{C}$ to $M_f(0)$ in the start stage of ϕ . But it is not clear about the relation between the electric resistance and the amount of M_ϵ , so that must be study in advance. The m is a constant and perhaps is a characteristic constant of alloys. We notice that the $R_{\phi=0}$ is also a function of temperature but now we can not find the formula. At $+7^\circ\text{C}$, the driving force of the phase transformation has maximum value. The driving force must vanish at temperature $M_f(0)$ because of the resistance of the phase transformation becomes so large. It is also true from equation (6) that the plastic deformation can not induce the $B2 \rightarrow M_\epsilon$ transformation at $M_f(0)$.

From the experimental point of view, we can conclude that the internal friction peak of phase transformation must occur at the time that the driving force of phase transformation is a maximum.

The curve above $+7^\circ\text{C}$ in Fig. 7. can be expressed as

$$b = a_0 + a_1 T + a_2 T^2 \quad (7)$$

Where the coefficient a_0 , a_1 , a_2 can be obtained from the coordinate values of three points in Fig. 7. Therefore, equation (5) can be expressed as

$$R = R_{\phi=0} \exp(-(a_0 + a_1 T + a_2 T^2)\phi) \quad (8)$$

This is also a dynamic law of the martensite M_ϵ induced by the plastic deformation from B2 phase above $+7^\circ\text{C}$ to $+13^\circ\text{C}$ in the start stage of ϕ . Equation (8) differs with equation (6) and means that the free energy G varies with the temperature above and below $+7^\circ\text{C}$ are not the same.

The ϕ_m (in Fig. 2.) may be considered as the final plastic deformation that induced the $B2 \rightarrow M$. After ϕ_m , the curves in Fig. 2. become straight lines that may explain as the $M_T \rightarrow M_\epsilon$ transformation induced by the plastic deformation.

(5) Below M_f the plastic deformation induces the $M_T \rightarrow M_\epsilon$ transformation.

The curves of -10°C to -39°C in Fig. 2. are a group of straight lines that can be expressed as

$$R = -n\phi + R_{\phi=0} \quad (9)$$

where the n is the slopes of straight lines and is a function of temperature that can be expressed as equation (7). This result can only be explained by the $M_T \rightarrow M_\epsilon$ transformation being induced because of plastic deformation. It is interesting that the $|n|$ ($=\partial R/\partial \phi$) increased on cooling; and means that the M_ϵ was induced by plastic deformation more easily at low temperature. The $B2 \rightarrow M_\epsilon$ can not be induced by ϕ below M_f . This result means that the electric resistivity of M_ϵ is smaller than M_T and it is concluded that the structure of M_ϵ differed slightly with M_T .

(6) When making torsional plastic deformation at different constant temperature from -39°C to $+42^\circ\text{C}$ following heating to $+80^\circ\text{C}$, the shape can be recovered to original state, i.e. the shape memory effect can be shown. We must conclude that the $B2 \rightarrow R_\epsilon$, $R_T \rightarrow M_\epsilon$, $B2 \rightarrow M_\epsilon$ and $M_T \rightarrow M_\epsilon$ have been induced by the plastic deformation on all these strain-induced phase transformation are the origin of shape memory effect.

CONCLUSIONS

(1) The $B2 \rightarrow R_\epsilon$, $R_T \rightarrow M_\epsilon$, $B2 \rightarrow M_\epsilon$ $M_T \rightarrow M_\epsilon$ can be induced by plastic deformation. When $T > A_s$, the plastic deformation can not induce the phase transformation and the M_d is equal to A_s almost.

(2) The M_s influence by plastic deformation according to

$$M_s(\gamma) = A_{s0} + M_s(0)$$

(3) In temperature range from M_s to M_f , the phase transformation dynamic of $B2 \rightarrow M_\epsilon$ according to exponential law in the start stage of ϕ .

(4) The structure of M_ϵ differs slightly with M_T .

(5) The internal friction peak must occur at the time that the driving force of phase transformation has maximum value.

REFERENCES

1. H. Warlimont, L. Delaey: Progress in Mat. Science., Vol. 28, P. 113. Pergamon Press, (1974).
2. H. C. Ling, R. Kaplow: Metall. Trans., 11A (1980) 77.
3. C. M. Hwang, M. Meichle, M. B. Salamon, C. M. Wayman: Res. Mechanica, 10, P1-23 (1984).
4. K. Charda, G. R. Purdy: J. Appl. Phys. 39 (1968) 2176.
5. Yuan-Ti Huang, Guo-Ping Yang, Ping He: Scripta Met., V. 19, No. 9 (1985) 1033, 1039.
6. D. Dejonghe, R. De Batist, L. Delaey: Scripta Met., V. 10 (1976) 1125.
7. H. C. Tong, C. M. Wayman: Scripta Met., V. 8 (1974) 93.